LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-JRNL-404111

# An Ion Doppler Spectrometer Instrument for Ion Temperature and Flow Measurements on SSPX

J. D. King, H. S. McLean, R. D. Wood, C. A. Romero-Talamas, J. M. Moller, E. C. Morse

May 22, 2008

Review of Scientific Instruments

# An ion Doppler spectrometer instrument for ion temperature and flow measurements on SSPX

**J.D. King, H.S. McLean, R.D. Wood, C.A. Romero-Talamás, J.M. Moller**
*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore CA, 94550 USA*

**E.C. Morse**
*University of California, Berkeley, Berkeley, CA*

## ABSTRACT

A high-resolution ion Doppler spectrometer has been installed on the Sustained Spheromak Plasma Experiment to measure ion temperatures and plasma flow. The system is composed of a 1 meter focal length Czerny-Turner spectrometer with diffraction grating line density of 2400 lines/mm, which allows for first order spectra between 300 and 600 nm. A 16-channel photomultiplier tube detection assembly combined with output coupling optics provides a spectral resolution of 0.0126 nm per channel. We calculate in some detail the mapping of curved slit images onto the linear detector array elements. This is important in determining wavelength resolution and setting the optimum vertical extent of the slit. Also, because of the small wavelength window of the IDS, a miniature fiber optic survey spectrometer sensitive to a wavelength range 200 to 1100 nm and having resolution 0.2 nm, is used to obtain a time-integrated spectrum for each shot to verify specific impurity line radiation. Several measurements validate the systems operation. Doppler broadening of C III 464.72 nm line in the plasma shows time-resolved ion temperatures up to 250 eV for hydrogen discharges, which is consistent with neutral particle energy analyzer measurements. Flow measurements show a sub-Alfvénic plasma flow ranging from 5 to 45 km/s for helium discharges.

## I. INTRODUCTION

Ion Doppler spectrometry (IDS) diagnostics been frequently applied to measure Doppler broadening and shifting of ion spectral lines in order to measure ion temperature and flow, respectively[1], and descriptions of Doppler measurements can be found in previous works[2]. For the ion temperatures <500 eV seen in SSPX, it is justifiable to use visible spectrometry to obtain core ion temperatures[3]. The shortcoming of these measurements is that they rely on line radiation of impurity particles rather than the majority species, therefore the ion temperature and flow of the majority species must be inferred from these measurements. Despite this, the IDS diagnostic measures ion temperatures comparable to other majority species temperature diagnostics such as charge exchange Neutral Particle Analyzers (NPA)[4], and warrants its use. In this work hydrogen and helium discharges were measured. He-II 468.57 nm and He-I 388.87 nm lines were measured in the helium discharges, and the difference in their flow velocities demonstrated successful operation of the IDS system.

A well-known property of Czerny-Turner spectrometers is that straight vertical entrance slits translate into curved spectrometer images at the exit plane[5, 6]. Such spectrometers use curved slits to compensate for this aberration, so the image at the exit plane is not curved and can be detected by a linear array. However, the aberration is unique to each grating angle and requires a unique slit curvature for each line considered. By reducing the vertical extent of our spectrometer slit, a single curved input slit was successfully mapped onto a vertical detection array with high enough resolution for a wide range of grating angles to be considered. This is important, since it allows for quick transition between a number of impurity lines without having to change the input slit.

## II. SYSTEM DESCRIPTION

The light collection system of the IDS is composed of a circular lens 30 mm in diameter with a 128 mm focal length. This lens was mounted to a platform, which allowed for 5 chord positions looking through a BK-7 glass port window, and provided direct visible access to the plasma. This setup can be seen in FIG. 1. The lens then focused the light onto the end of a custom-built fiber bundle, located at the focal length. At the collection end of the fiber bundle, the cable's 24 individual 0.25 mm silica fibers were oriented in a hexagonal pattern (1.00 mm sides) to optimize light collected from the plasma. On the spectrometer side of the fiber bundle, the fibers were stacked linearly in a single row with area of 0.25mm × 6 mm. This area of light was then coupled to the spectrometer by two mirrors, which illuminated a slightly curved vertical input slit.

The spectrometer used was a Jobin Yvon THR 1000 Czerny Turner 1 meter focal length high-resolution spectrometer with dispersion at the exit plane of 0.331 nm/mm. The diffraction grating had a line density of 2400 lines/mm blazed to optimize the spectral region between 300 and 600 nm.

Wavelength dispersion beyond that of the spectrometer was needed to resolve the expected 0.04 nm line widths. An 8 mm focal length plano-convex lens was used to magnify the light exiting the spectrometer to a final dispersion of 0.0126 nm/mm at the PMT face. The PMT used was a Hamamatsu 16 Channel PMT R5900U-L16 Series. The channels were arranged in a linear array, with each channel having a height of 16 mm, and a channel pitch of 1 mm, allowing for expected line widths to be spread across a minimum of 3 channels. Also, for anticipated flows of <100 km/s, the corresponding

Doppler shift of 0.125 nm is within the total PMT window width of 0.201 nm. This allowed for both temperature and flow to be measured simultaneously.

The output of each PMT channel was connected to 4×4 channels CAMAC digitizers in an electronics crate, by 15 m of 50 Ω coaxial cable. These cables were terminated such that signal ringing was negligible. The resultant voltage pulse was than converted to a digital signal, and stored in computer memory.

An Ocean Optics HR4000[7] fiber-optic survey spectrometer (FOSS) provided a time-integrated spectrum over a range of 200 to 1100 nm for each shot taken. Because of the dynamic transition of impurities over multiple shots, it was necessary to have a way to predict the strongest impurity line radiation of each shot. This was achieved by reviewing the previous shot's FOSS spectra and identifying observed lines.

## III. SLIT GEOMETRY CONSIDERATIONS

Each grating angle of the spectrometer requires it's own unique slit to map a vertically straight output image. Because multiple impurity lines, and therefore multiple grating angles, were measured in a given run day it was important to determine a general method of reducing the curvature aberration without replacing the slit. This was achieved by reducing the vertical extent of the slit. A calculation of the width of an output image that has the same radius of curvature as the input slit is presented here. From simple geometrical arguments the effect of magnifying this curvature can be approximated by

$$(R-L)^2 + \left(H/2\right)^2 = R^2, \tag{1}$$

and

$$\Delta = M(L+d). \tag{2}$$

Here $R$ is the radius of curvature, $L$ is the width the curvature assumes, $H$ is the height of the slit (or vertical extent), Δ is the total image width after magnification, $M$ is the magnification from the plano convex lens, and $d$ is the slit size. All parameters are shown in FIG 2. Combining equations (1) and (2) gives,

$$\Delta = M\left(R - \sqrt{R^2 - \left(H/2\right)^2} + d\right) \quad . \tag{3}$$

The vertical extent and slit size were reduced to 1.00 mm, and 10 μm, respectively. The spectrometers slit radius of curvature was measured to be 8.9 cm. For imaged light with a radius of curvature of 8.9 cm, Δ = 0.30 mm. This means that the total image width of a single wavelength at the PMT face is about 1/3 the width of a single channel. The smaller slit and vertical extent increased the spectrometer resolution[2] to a linewidth of 0.025 nm for a Hg calibration line at 366.33 nm, which is nearly identical to the resolution of other instruments of this type.[8] This means that the resolution of the IDS is sufficient to provide accurate broadening measurements for any line within the wavelength window 300 to 600 nm, without having to match the slit curvature to the grating angle. This increase in resolution did come at the expense of a 5 times reduction in light throughput.

## V. SAMPLE MEASUREMENTS

A sample temperature measurement of C III 464.72 nm line is shown in FIG. 3. The highest ion temperature coincides with the greatest gun voltage. The signal-to-noise was low following the gun voltage drop at 0.65 ms, and could not be used to obtain temperature information. Also, the neutral H-$\beta$ 486.13 nm line was measured and had an ion temperature less then 8 eV throughout an entire shot. This is an expected result, and provides a check into the validity of the temperature measurement, as the H-$\beta$ emissions tend to originate from the cold outer edge of the plasma whereas the twice-ionized C III exists near the much hotter center. The raw data from each time slice was fitted to a gaussian to obtain the line width for each temperature measurement, and the $R^2$ values for these fits were > 0.95 for all data reported. The C III ion temperature ranges from 40 to 250 eV, which is comparable to the 110 eV ion temperature of the majority species hydrogen measured previously by the SSPX compact NPA[9].

Flow measurements consisted of two chord measurements, one pointing perpendicular to the toroidal direction, and one pointing $16.767^0$ offset from the perpendicular position. The orientations of the chords are shown in FIG 1. The $16.767^0$ chord provides a component of the chord path that was oriented parallel to the toroidal direction allowing for Doppler shifting to be measured.

The flow measurements used exclusively helium discharges, allowing for two ionization states from the same majority species to be considered, which were He I 388.87 nm and He II 468.57 nm. A Doppler shift in line centroid of 0.095 nm can be seen in FIG. 4 for one time slice of He II flow measurement. Flow of He II was found to peak around 45 km/s at the beginning of the shot and monotonically decrease to about 5 km/s. No flow was observed for He I. This serves as a check to the successful operation of the device as the neutral He I is not influenced by the confining magnetic fields, and therefore will not follow the same toroidal trajectory as the singly ionized He II.

## ACKNOWLEDGEMENTS

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract

DE-AC52-07NA27344.

[1] D.J. Den Hartog, and R.J. Fonck, Rev. Sci. Instrum. 65, 3238 (1994).

[2] P. Gu, M. Nagata, K.J. McCollam, T.R. Jarboe, B.A. Nelson, A.J. Redd, Rev. Sci. Instrum. 75, 1337 (2004).

[3] A. Graf, M. May, P. Beiersdorfer, E. Magee, M. Lawrence, J. Rice, Rev. Sci. Instrum. 75, 10 (2004).

[4] R.M. Mayo, J.C. Fernandez, I. Henins, L.S. Kirschenbaum, C.P. Munson, F.J. Wysocki, Nucl. Fusion 31 (1991) 2087.

[5] D. Craig, D.J. Den Hartog, D.A. Ennis, S. Gangadhara, D. Holly, Rev. Sci. Instrum. 78, 013103 (2007).

[6] N.C. Das, Applied Optics Vol. 30, No. 25, (1991).

[7] Ocean Optics Inc., http://www.oceanoptics.com/.

[8] H. Sakakita, S. Kiyama, Y. Hirano, Y. Yagi, H. Koguchi, S. Sekine, T. Shimada, I. Hirota, Y. Maejima, Rev. Sci. Instrum. 74, 2111 (2003).

[9] E.D. Mezonlin, S. Roberson, C. Raynor, R. Appartaim, J.A. Johnson III, V.I. Afanasyev, S.S. Kozlovsky, J.M. Moller, D.N. Hill, E.B. Hooper, H.S. McLean, and R.D. Wood, Rev. Sci. Instrum. 78, 053504 (2007).

## FIGURE CAPTIONS

**FIG. 1**. A top view of SSPX, showing the 5 possible chord paths of the IDS.

**FIG. 2.** The relevant geometrical parameters of the curved slit before magnification.

**FIG. 3.** Top three plots are the discharge parameters of shot 20387. The bottom shows the C III ion temperature for shot 20387 measured by the IDS.

**FIG. 4.** A single time slice of He II 468.57 nm line for shots 20868 and 20869. Red corresponds to the radial chord, and blue to the 16.767$^0$ chord, at time 0.134 ms.

## FIGURES

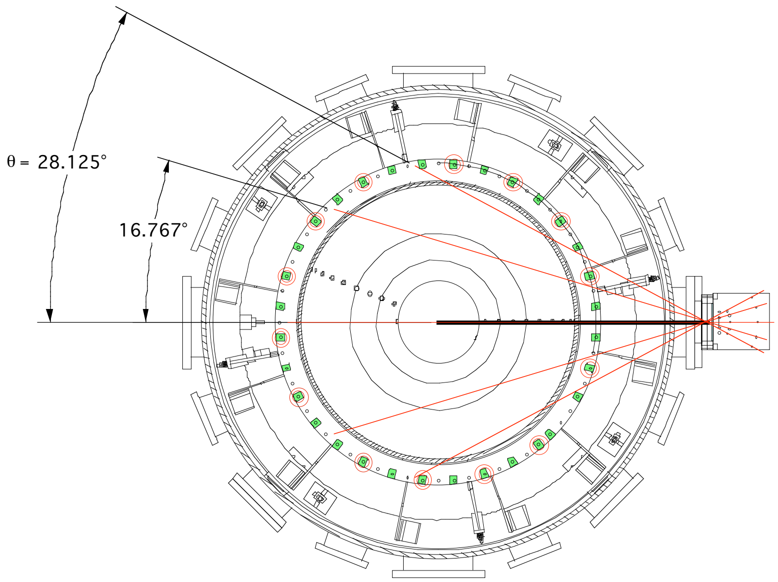


**FIG. 1:**

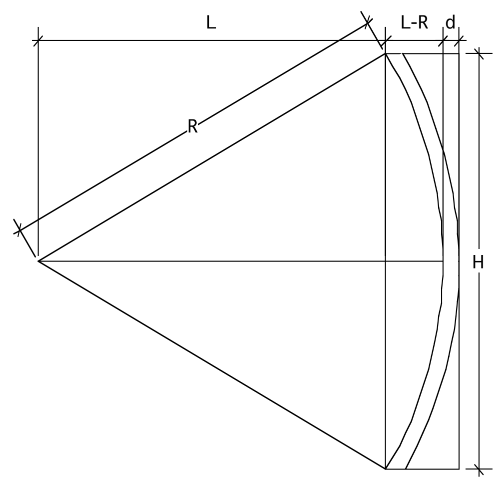


**FIG. 2:**

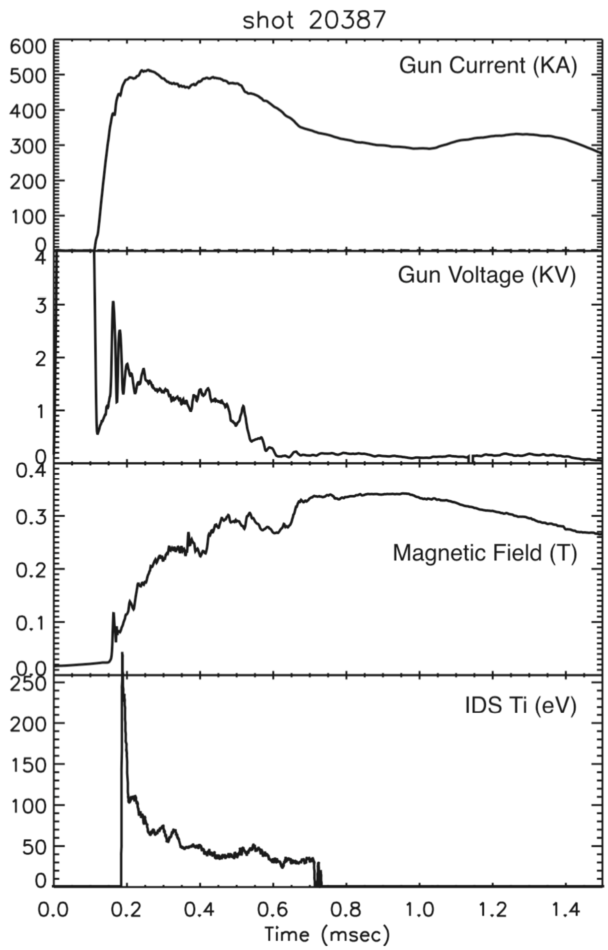
shot 20387
Gun Current (KA)
600
500
400
300
200
100
0
Gun Voltage (KV)
4
3
2
1
0
Magnetic Field (T)
0.4
0.3
0.2
0.1
0.0
IDS Ti (eV)
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Time (msec)

**FIG. 3:**

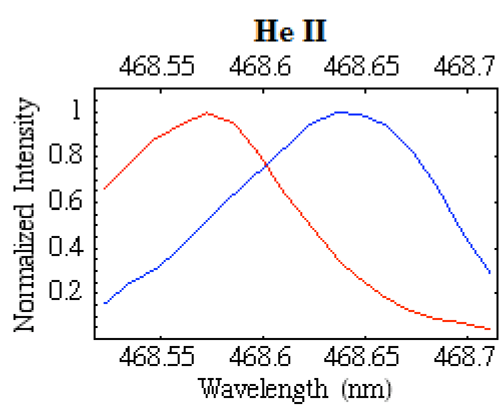
He II
468.55
468.6
468.65
468.7
Normalized Intensity
1
0.8
0.6
0.4
0.2
Wavelength (nm)

**FIG. 4:**